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PROPAGATION EFFECTS ON SATELLITE COMMUNICATION SYSTEMS OPERATING IN THE RANGE OF 240 TO 3000 MEGAHERTZ

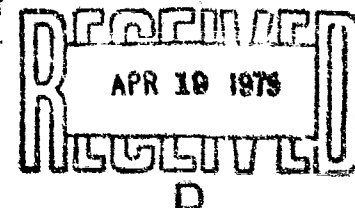Avionics Communications Branch
System Avionics Division

October 1978

TECHNICAL REPORT AFAL-TR-78-145

Final Report for Period October 1976 to October 1977

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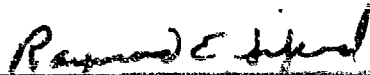
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report provides systems designers with information on propagation effects in the 240 MHz to 3 GHz frequency range which may affect satellite communication link operations.

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FOREWORD

This report was prepared by Mr. Wade T. Hunt of the System Avionics Division, Air Force Avionics Laboratory, under Project 1227, "Communication Systems Concepts and Technology." Mr. Allen L. Johnson is Project Engineer.

The help and suggestions of Mr. Johnson in writing and organizing the text is greatly appreciated. Also the data supplied by Mr. Roger Winn, AFAL Staff meteorologist, and Mr. Raymond Wasky, AFAL/RWT (Fire Control Branch), from which the attenuation vs elevation through rain curves were derived, is greatly appreciated.

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SECTION I

INTRODUCTION

This report was written to provide system designers information on propagation effects in the 240 MHz to 3 GHz frequency range which may affect satellite communication link operations.

In this frequency range, propagation effects that may affect satellite links are (1) ionospheric effects, (2) tropospheric effects, (3) attenuation due to precipitation, (4) multipath, (5) foliage, and (6) ambient noise. These propagation phenomena can affect both the phase and the amplitude of the propagated signals. These effects and their magnitudes must be known to the system designer so that system margins can be provided to overcome them. Also, methods of transmission coding and modifying operating procedures may be employed to overcome these effects if system design parameter information such as auto-correlation function, delay spread, etc. are known. Therefore, such design information as is available is presented in this report.

SECTION II

IONOSPHERIC EFFECTS

1. SCINTILLATION FADING

Fluctuation in amplitude believed to be caused by variations in ionospheric structure is termed scintillation fading. It is dependent on radio frequency, geographic position, and geomagnetic conditions.

Equatorial scintillation is characterized by very deep and rapid fading at the lower UHF band frequencies (e.g., 300 MHz) and is largely constrained to night-time activity, commencing after local sunset and continuing into the morning hours in some cases. Both fading range and rate tend to decrease as the night wears on. Activity tends to peak at the equinoxes and null at the solstices.

During the autumnal equinox period, nonfading conditions can be expected 90% of the 24 hour day. Heavy fading can be expected 7 to 10% of the time. Depth of fading of 25 dB peak-to-peak are the rule rather than the exception during the fading period. The differential delay of the various components of the fading signal appears to be less than 1 microsecond, indicating differential path distances of only a few meters (Reference 1). Measurements were made in the region 15-20° North and South of the magnetic equator.

During the period of fading, sufficient margin is not available to overcome the 25 dB or greater peak-to-peak fades. Antenna separation of 500 meters to 1 kilometer is required to obtain sufficient space diversity to operate through the fading periods. The coherent bandwidth of the fading appears to be 25 to 100% of the center frequency, making frequency diversity costly as a technique for overcoming the fading. Antenna polarization diversity, likewise, does not reduce the fading. Therefore, about the only means left for overcoming the fading is a time diversity or coding diversity with extremely long error correction codes or message repeating. During periods of flight testing the duration of outage in the aircraft for each fade appears to be one second or less, thereby giving a reasonable limit for the construction of error correction codes or message repeating techniques (Reference 2).

For geometric latitudes 50° and above, curves showing required system margins as a function of frequency have been derived at Cambridge Research Center* using ionospheric irregularity models developed by Fremouw and Rino (Reference 3) and Pope (Reference 4). The intensity of the resulting amplitude and phase fluctuations of a signal at the earth's surface were computed using the diffraction theory developed by Briggs and Parkin (Reference 5). These results were then used (Reference 6) to derive the fading margins necessary to obtain specified system avail- abilities. Results were modified slightly to achieve best overall agree- ment with measurements made by CRC (Reference 7) at 254 and 1550 MHz at Ottawa, Churchill, and Resolute Bay. Results are shown in Figures 1, 2, and 3 for required system availabilities 90%, 99%, and 99.9% respectively. These curves are valid for propagation paths having an azimuth of 180° at the ground terminal (spacecraft on ground station's central meridian). For propagation paths which are not on the ground station's central meridian it is necessary to modify the results presented in Figures 1, 2, and 3 to account for the increased propagation path-length through the ionosphere and for aspect sensitivity. For the path-length correction Figure 4 shows a plot of Δ, the amount by which the fading margin in dB as determined from Figures 1, 2, and 3 is to be multiplied, as a function of α, the angular distance between the ground station central meridian and the line-of-sight to the satellite. These curves may require modification in certain cases for sites where aspect sensitivity becomes important. These fading margins are for long term averages of specified system availabilities. For short periods of time, however, the inten- sity of fading may greatly exceed the long term average. Fading margins required for specified system availability during the worst single hour of each day have been determined, using CRC measurements, to be a factor of approximately 2 (in dB) higher than those required over the long term.

In mid latitudes (±20° to ±50°) ionospheric scintillation is rare and can be ignored in most system planning exercises.

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*Now the Air Force Geophysics Laboratory.

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2. FARADAY ROTATION

If transmission from the satellite or aircraft is linearly polarized, the plane of polarization will rotate at a rate dependent on the transmission frequency, angle between the earth's magnetic field, the direction of propagation, and the integrated electron density traversed by the path. At UHF frequencies the rotation can cause prohibitive transmission outages if linearly polarized antennas are used at both ends of the link. The ideal solution is to provide circular polarized (CP) antennas at each end. If circular polarization is used at one end and linear polarization at the other, a 3 dB polarization loss results.

SECTION III

TROPOSPHERIC EFFECTS

1. LAYERS

In the case of air-to-air propagation, it has been observed that the signal would fade out long before the radio horizon intervened between airborne transmitter and receiver, and then, after further separation of perhaps 50 to 100 miles, would reappear, and might even continue out to long past the normal radio horizon.

This, principally, is a tropospheric phenomenon and affects UHF signals primarily to ranges of less than 300 miles.

In the early nineteen fifties the Aircraft Radiation Lab located at Wright-Patterson AFB flew a number of flights to measure aircraft-to-aircraft propagation effects. Also in the early nineteen fifties, Ming Wong developed ray tracing techniques for tracing the paths of the rays through the troposphere (Reference 8).

This phenomenon has been observed more at the higher frequencies than at UHF.

2. DUCTING

Ducting is caused by the presence of an inversion layer in the atmosphere, which results in a trapping or waveguide effect, sometimes extending the transmission range well beyond the line-of-sight, and often resulting in severe fading.

On one occasion the ASD (Aeronautical Systems Division) aircraft flying over Hawaii was able to establish successful communications when the satellite was at a negative 11-degree-look angle.

SECTION IV

MULTIPATH FADING

Since 1966 UHF satellite communication testing has been conducted using the LES-3, LES-5, LES-6, and TACSAT satellites. As a result of over 1000 flight test hours in a C-135 type aircraft, information has been obtained on the depth of multipath fading experienced when operating an airborne terminal over a SATCOM link.

Multipath fading results are dependent on the type of reflecting surface which produces the multipath. Multipath has been experienced from the following types of surfaces:

    a. Broken - mountainous terrain

    b. Flat - smooth terrain

    c. Aircraft surfaces

    d. Large lakes

    e. Frozen salt water or frozen fresh water

    f. Oceans

UHF multipath fading on an air-to-satellite link over mountainous terrain is minimal. Since mountainous terrain does not present a good reflecting surface, multipath is seldom observed, regardless of the elevation angle between the aircraft and the satellite. There may be an occasional glint which causes a few dB fading for a few seconds, but, in general, the fading is less than 1 dB for mountainous terrain.

Multipath fading from flat, smooth terrain follows the diffuse reflection model. The multipath signal is a combination of many separate rays which are coherent. The resulting fading has a Rayleigh appearance with an average depth of 1 or 2 dB and an occasional glint causing a 5 or 8 dB fade. The duration of the deeper fade is usually a second or two and occurs less than one percent of the time.

Reflections from aircraft surfaces cause multipath fading when the aircraft/satellite relation is such as to cause a wing or tail to be in a position which provides a low grazing path for the reflected signal. On one UHF SATCOM antenna elevation flight test, 3 to 8 dB of multipath

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fading was observed when the satellite was within 5° of the aircraft tail, at elevation angles from 0° to 30°. Similar multipath fading was noted over 5° of azimuth as the wingtip was pointed toward the satellite. This also occurred for elevation angles from 0° to 30°.

On flights over large lakes, frozen fresh water, or frozen salt water (Arctic and Antarctic) multipath fading has been observed which is quite similar to that experienced on the open ocean. The extent of the multipath fading is limited by the size of the lake.

Over the ocean the fading model is primarily a specular reflection resulting in a two-ray multipath condition. As the distance from the satellite to the aircraft changes, the multipath fading is very cyclical as the direct and reflected ray oscillate between in-phase (enhancement) and out-of-phase (null). At low elevation angles the ocean looks very smooth to the UHF radio wave. Even a rough ocean looks smooth because at the low angle you are just seeing the tops of the waves and not the troughs. All the satellite tests were conducted with circular polarization except LES-3. With the LES-3, linear polarization fading which approached 25 dB at elevation angles below 10° was observed. However, with circular polarization on LES-5, LES-6, and TACSAT, fading which exceeded 10 dB was seldom observed. It appears that the circular polarization provides a degree of polarization diversity which reduces the fading depth. In general, an average of 3 dB of fading at minimum elevation angles was noted. The fading increased to 8 or 10 dB at an elevation angle between 10° and 15° and then dropped off to one dB or less at high elevation angles. A plot of the best estimate of the fading characteristics versus elevation angle is given in Figure 5. This is a heuristic chart developed from data reported in the reference reports and a best guess from the thousands of hours of testing performed since 1967.

The degree of multipath fading experienced is dependent on the antenna used and its exact placement on the aircraft. If the antenna has poor gain in the direction of the multipath reflection, then the fading will be minimized. In recent antenna tests it was noted that one antenna would experience multipath from the aircraft surface while the

other six antennas under test saw no multipath at that particular elevation/
azimuth angle. Not only the gain toward horizon is important but also the
polarization. All antennas have an axial ratio, and the exact relation
of horizontal polarization to vertical polarization is important with
respect to multipath. Therefore, the multipath fading in Figure 5 is an
average for a wide variety of antennas (blades, crossed dipoles, spirals,
crossed slots, turnstile, double-tuned stubs, and dual mode) and a wide
variety of antenna placements on the aircraft (Reference 9).

Figure 6 is a plot of two-ray multipath fading rate and delay that
can be expected. A fade margin of 20 dB has been proved necessary
for UHF satellite communication systems operating in the multipath
environment.

SECTION V

ATTENUATION DUE TO PRECIPITATION

Figure 7 is a plot of attenuation (dB/km) to rainfall rate (mm/hr) for various rainfall rates. The attenuation is on the order of 0.025 dB/km for very heavy rain at 3000 MHz. Because of the longer wavelengths involved, attenuation due to precipitation and water drops is not nearly as bad at the longer wavelength (i.e., 3000 MHz as it is at 10 GHz and above).

From Figure 7 data on dB per kilometer for 3000 MHz, graphs of attenuation vs. elevation angle were constructed for 3000 MHz, through moderate rain (Figure 8), heavy rain (Figure 9), and very heavy rain (Figure 10), using the exponential atmospheric model and a path length of 2000 ft above the average freezing level height for spring, summer, and fall for Wright-Patterson Air Force Base.

Figure 10 is based on looking through a typical convective-type thunderstorm which is approximately 10 miles in diameter. Below 3000 MHz the effects of attenuation are very minimal even for a very heavy rain.

SECTION VI

LONG TERM MEDIA BASIC TRANSMISSION LOSSES

Propagation of radio frequency energy at UHF is affected by the troposphere, specifically by variations in the refractive index of the atmosphere. The terrain along and in the vicinity of the great circle path between transmitter and receiver also play an important part. Methods given by Rice et al (1967), which include a statistical allowance for the effects of terrain and atmosphere on long term media basic transmission loss, were used to develop the curves in Figures 11, 12, 13, and 14 (Reference 10).

SECTION VII

FOLIAGE

A user, employing a man pack or vehicular set which may be operated
in a forest or jungle, is interested in the probability or likelihood of
the additional attenuation due to foliage being beyond the sets design
margin. This is especially true for digital communication links where
a few dB can make the difference between a workable and nonworkable link.
The data that would be useful in this instance is the probability density
function of the additional attenuation loss that will be experienced on
entering a forest compared to flat open ground.

The probability density function (PDF) of attenuation loss due to
the forest is shown in Figure 15 and has a mean value of 8 dB. The
cumulative distribution of the probability of the attenuation being
greater than the ordinate was derived from Figure 15 and is shown in
Figure 16 (Reference 17). The curves are based on measured data in the
forest of the United Kingdon (UK).

From this, it would appear, for example, that the probability of
10 dB being exceeded is 0.2 when any random choice of site is chosen.
Conversely there is a probability of 0.8 that the attenuation would be
less than 10 dB. Similarly, if the design specification requires a 0.95
probability of success, then the design would require a margin of approx-
imately 14 dB. Also from Figure 16 can be calculated the average number
of sitings required for a given margin. For example:

ALLOWED MARGIN	AVERAGE NUMBER OF ANTENNA SITING ATTEMPTS
15 dB	1
7 dB	2
5.5 dB	3
2 dB	50

In practice, however, the situation may not be so pessimistic.
Moving around the forest will result in a series of maximum and minimum

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values for a given antenna height. Thus, if the first site chosen happened to give a 14 dB degradation, then by moving a short distance a much more favorable situation would be found. From observations made, the distance between the first and second locations would probably be less than 10 meters in practice.

Experimental data compare favorably to theoretical values reported in the literature (References 11, 12) where losses of 13 dB can be expected behind a tree of 50-cm diameter at a frequency of 254 MHz. For tree heights of 20 meters and a satellite elevation angle of 22°, the maximum path length through the foliage is approximately 50 meters. The average attenuation in the forest was found to be 8 dB, giving a value of 0.16 dB/meter if foliage attenuation was the sole factor. This can be compared with the figure of 0.08 dB/meter in Reference 13 and the 0.3 dB/meter in Reference 12.

SECTION VIII

AMBIENT NOISE

1.   GALACTIC AND SOLAR NOISE

Galactic and solar noise (References 13, 14) reaching the surface of
the earth extends from about 15 MHz to 100 GHz, since it is limited at
the low end of the spectrum by ionospheric absorption and at the high
end by atmospheric absorption. In many cases, the importance of this
noise is restricted by atmospheric noise to frequencies not lower than
about 18 MHz, and by receiver noise and antenna gain to frequencies not
higher than about 500 MHz. However, with a high-gain receiving antenna
pointed at the sun, the antenna noise temperature may exceed 290°K at
frequencies as high as 40 GHz. Figure 17 shows galactic and solar noise
levels in dB relative to a noise temperature of 290°K, when receiving on
a half-wave dipole, for frequencies between 100 MHz and 10 GHz which
cover the 240-3000 MHz portion of the spectrum in which we are interested.

The levels of cosmic noise received by a directive antenna pointed
at a noise source may be estimated by correcting the relative noise
levels as measured on a half-wave dipole for the actual receiving antenna
gain realized on the noise source. Since the galactic plane is an ex-
tended non-uniform noise source, free-space antenna gains cannot usually
be realized, and 10-15 dB is approximately the maximum antenna gain that
can be realized in this case. However, for the sun, (and a number of
other discrete cosmic noise sources which are scattered about the sky)
antenna gains equal to the theoretical free-space values may be realized.

2.   AMBIENT NOISE DUE TO ABSORPTION BY THE TROPOSPHERE
AND BY PRECIPITATION

At microwave frequencies, precipitation and the atmospheric gases are
significant in the design of communication systems, because of both their
absorption and the increased antenna temperature which results from their
"black body" radiation. At lower frequencies, these effects are so small
that they are not normally tabulated below 1 GHz. However, for very
small elevation angles the antenna noise temperature will show some
increase due to tropospheric thermal noise. At 2° elevation and 1 GHz
this amounts to about 30°K (Figure 18), decreasing to less than 2°K for
the same elevation angle and a frequency of 100 MHz (Reference 15).

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SECTION IX

SUMMARY AND CONCLUSIONS

In the past, various propagation effects have been taken into account by the system designer by allowing for system margin, i.e., increased power over that required for free-space propagation signal-to-noise ratio. However, many of these effects cannot be overcome simply by increasing the power. Therefore, propagation phenomena must be taken into consideration in the original system design. This work is a compilation of data from a number of sources in order to bring together in a concise form the kind of propagation phenomena system designers must take into consideration when designing systems in the 240 to 3000 GHz frequency range.
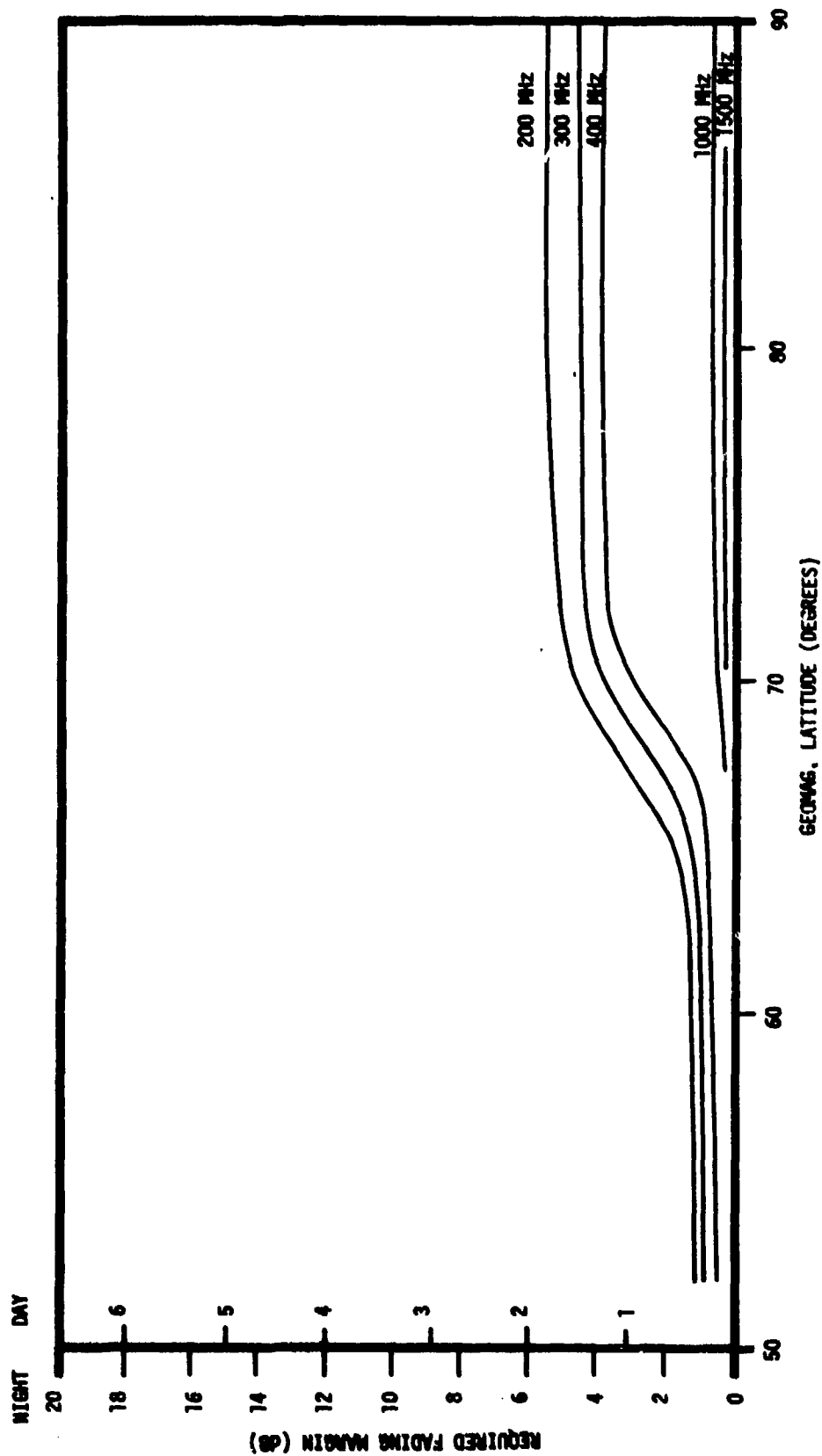
Figure 1. 90% System Availability
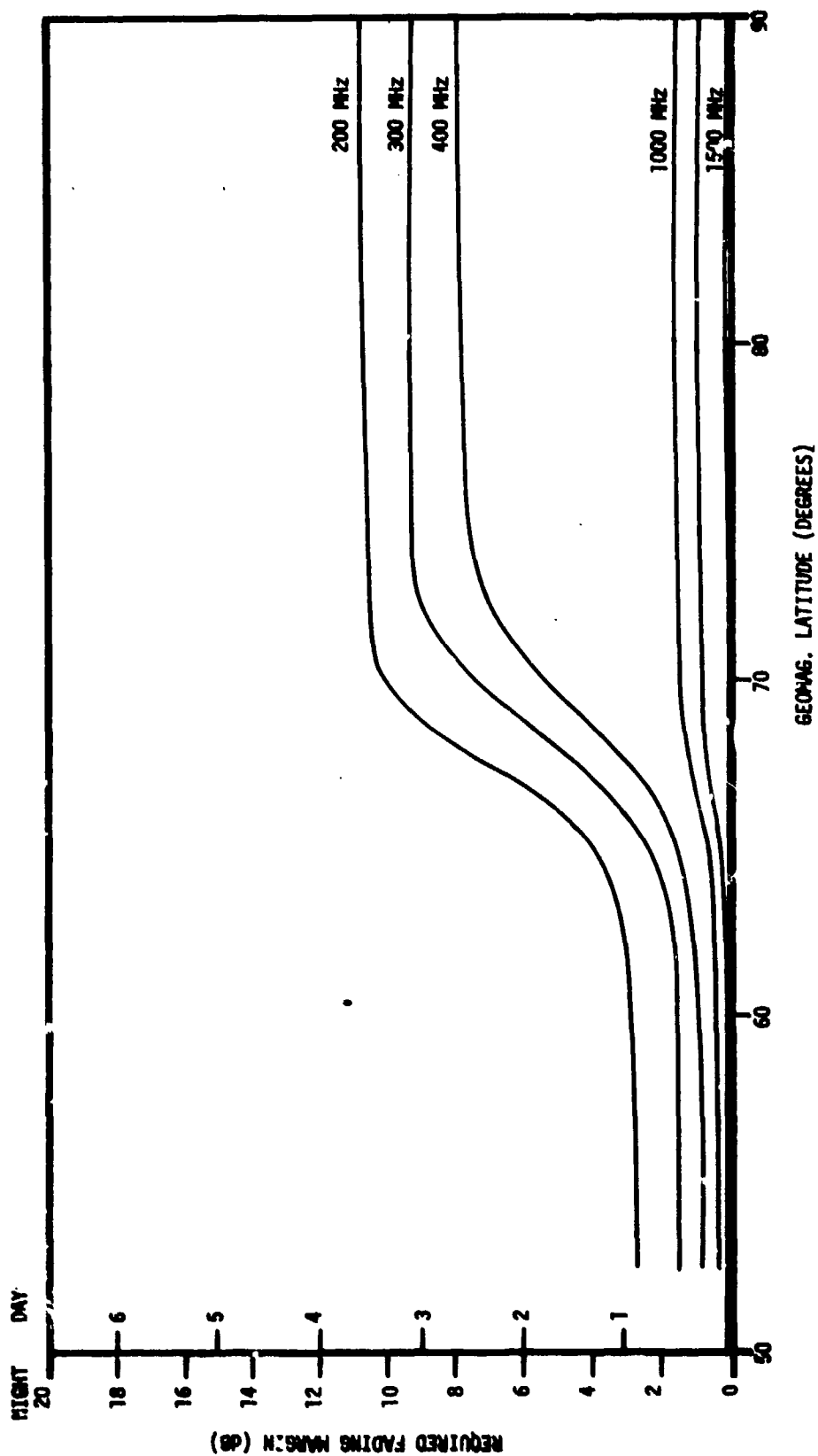
Figure 2. 99% System Availability
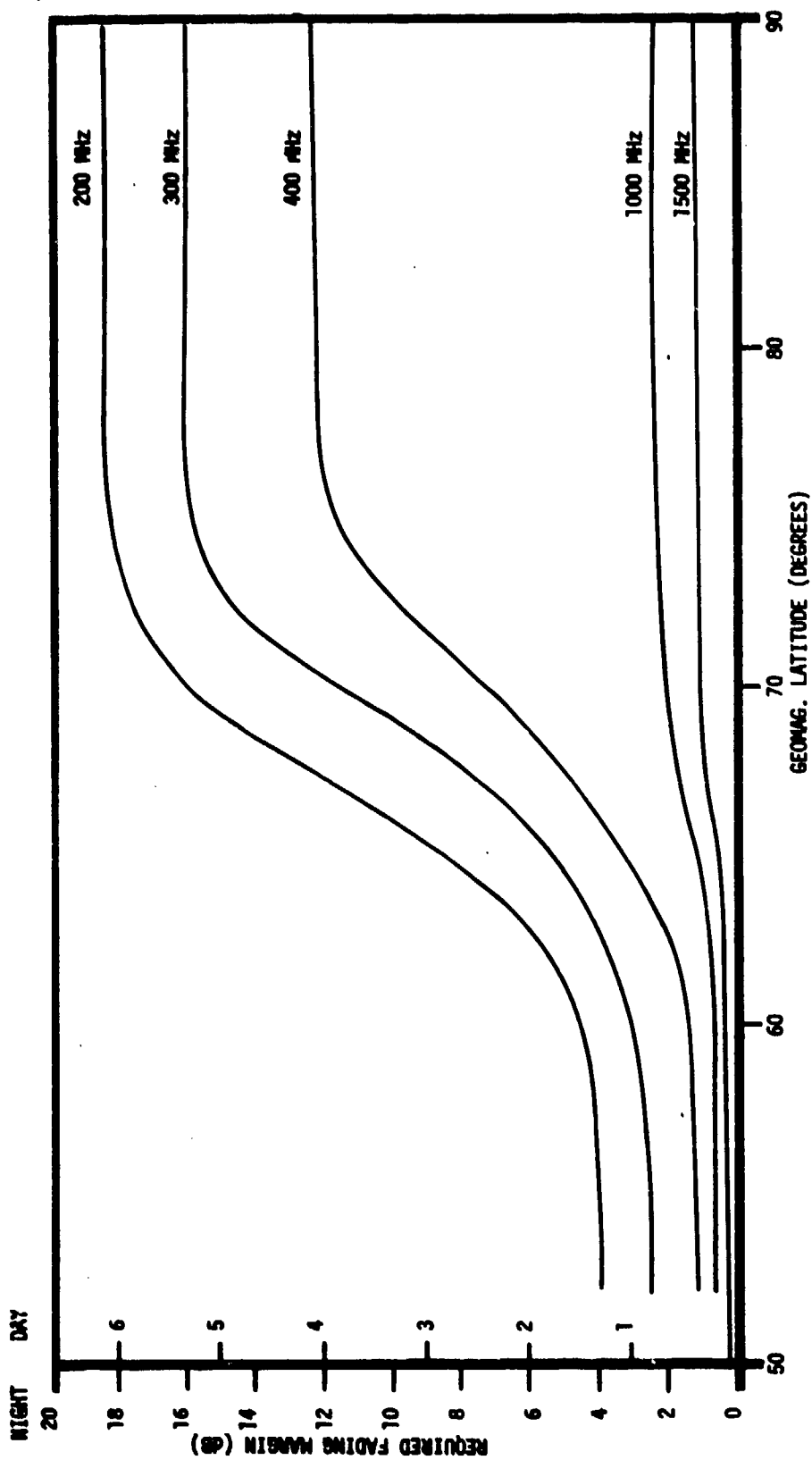
Figure 3. 99.9% System Availability

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α : angular distance between LOS to satellite and central meridian

Δ : total fading margin = Δ x fading margin satellite on central meridian

$75^O < \alpha \leq 90^O$

$45^O < \alpha \leq 75^O$

$\alpha \leq 45^O$

GEOMAG. LATITUDE (DEGREES)
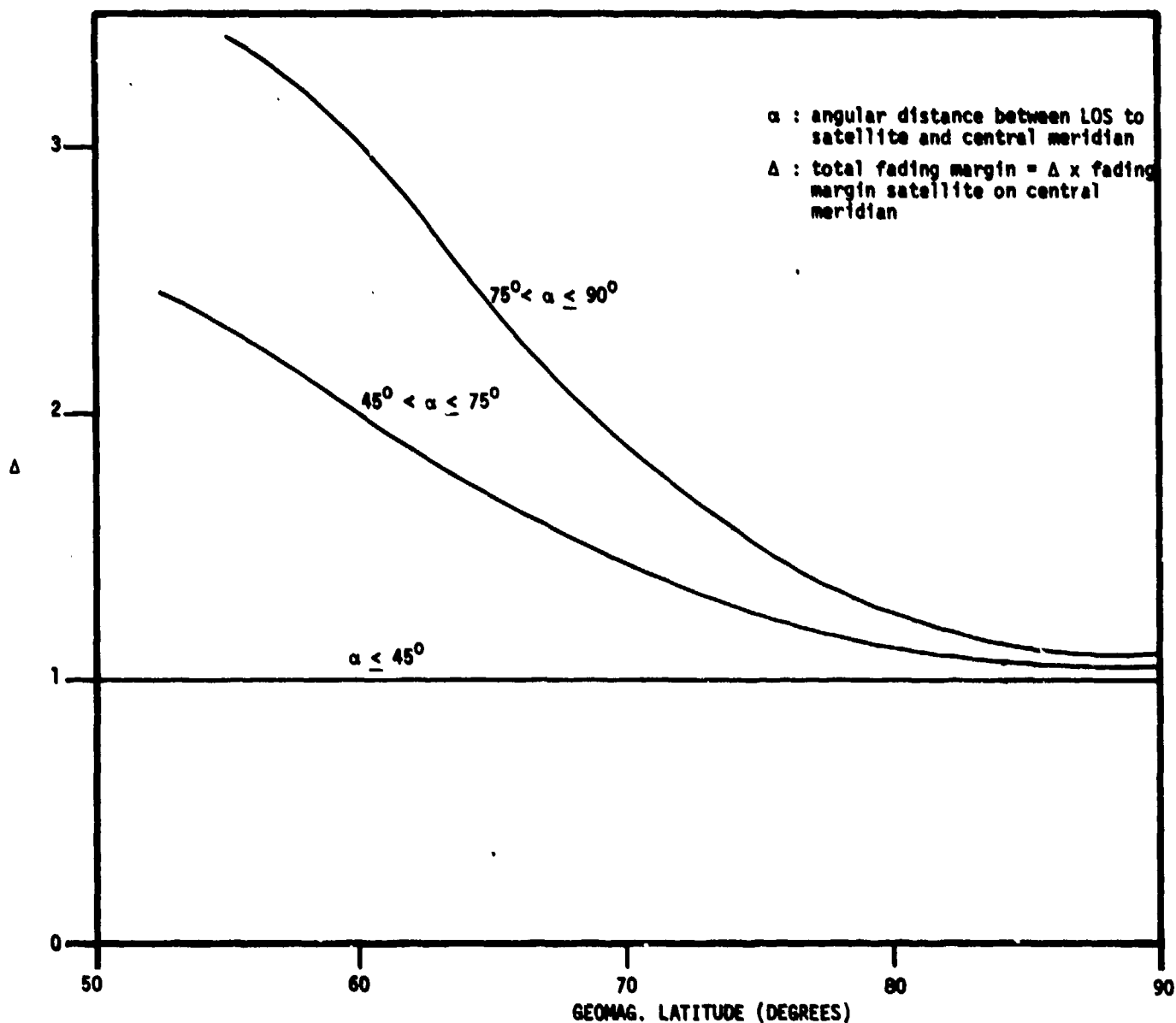
Figure 4.   Fading Margin Correction Factor for Satellite Not on Observers Central Meridian

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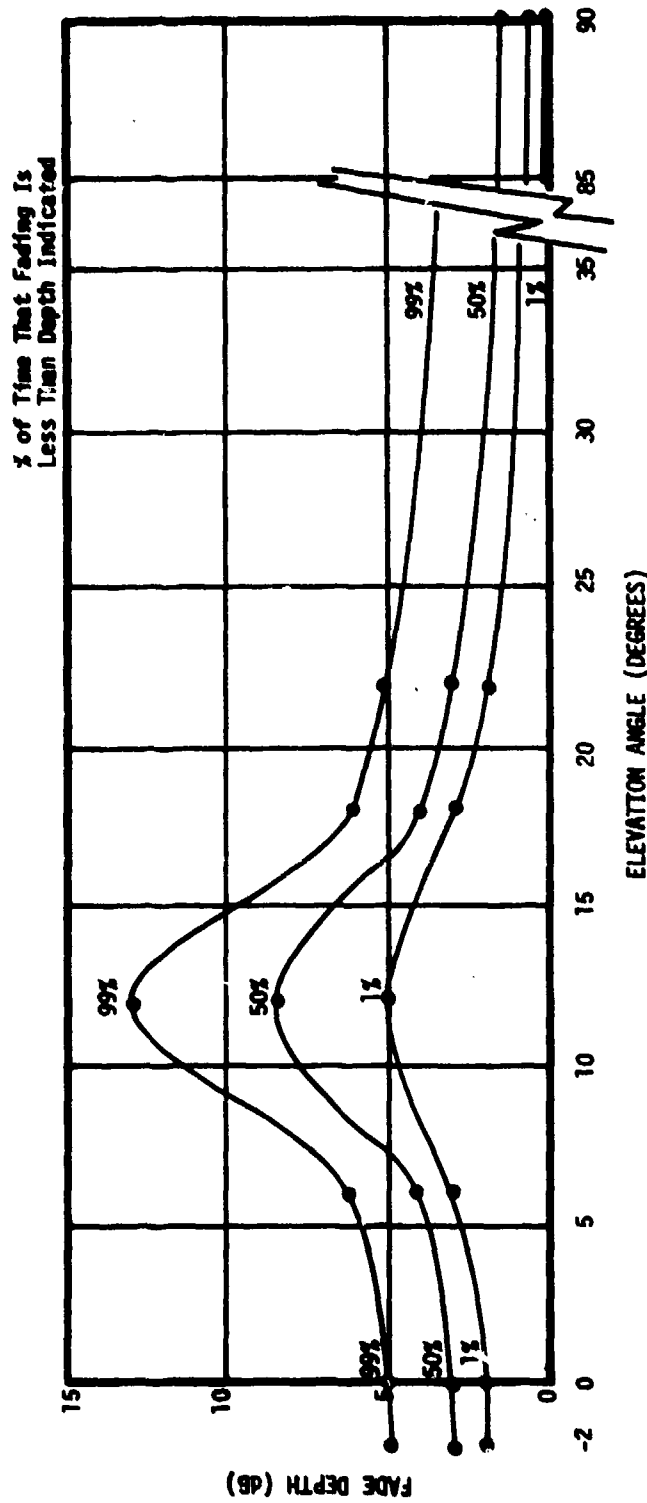
Figure 5. Multipath Fading Depth
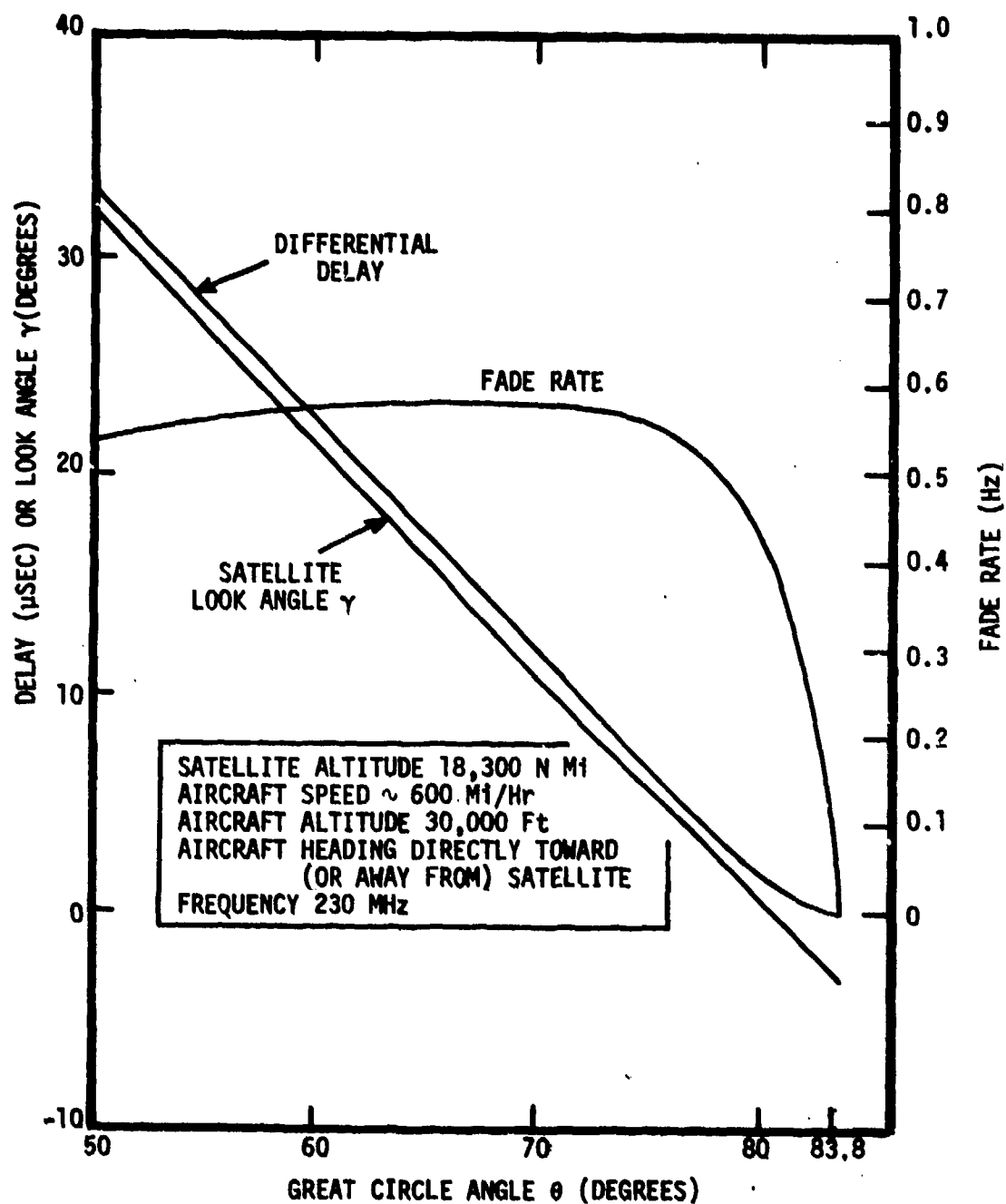
Figure 6. Two-Ray Multipath Fading Rate and Delay
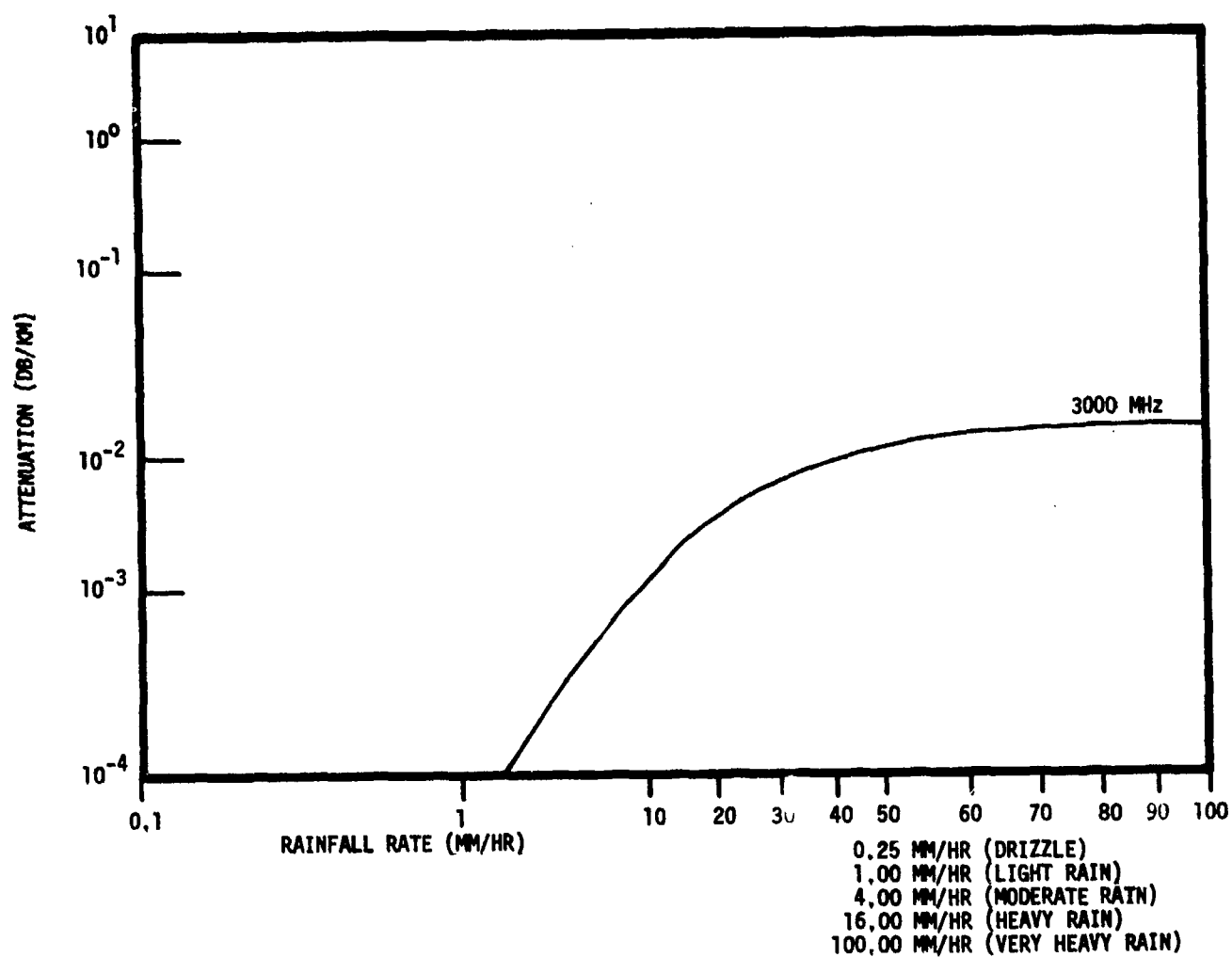
Figure 7.   Rainfall vs Attenuation Coefficients for 3000 MHz
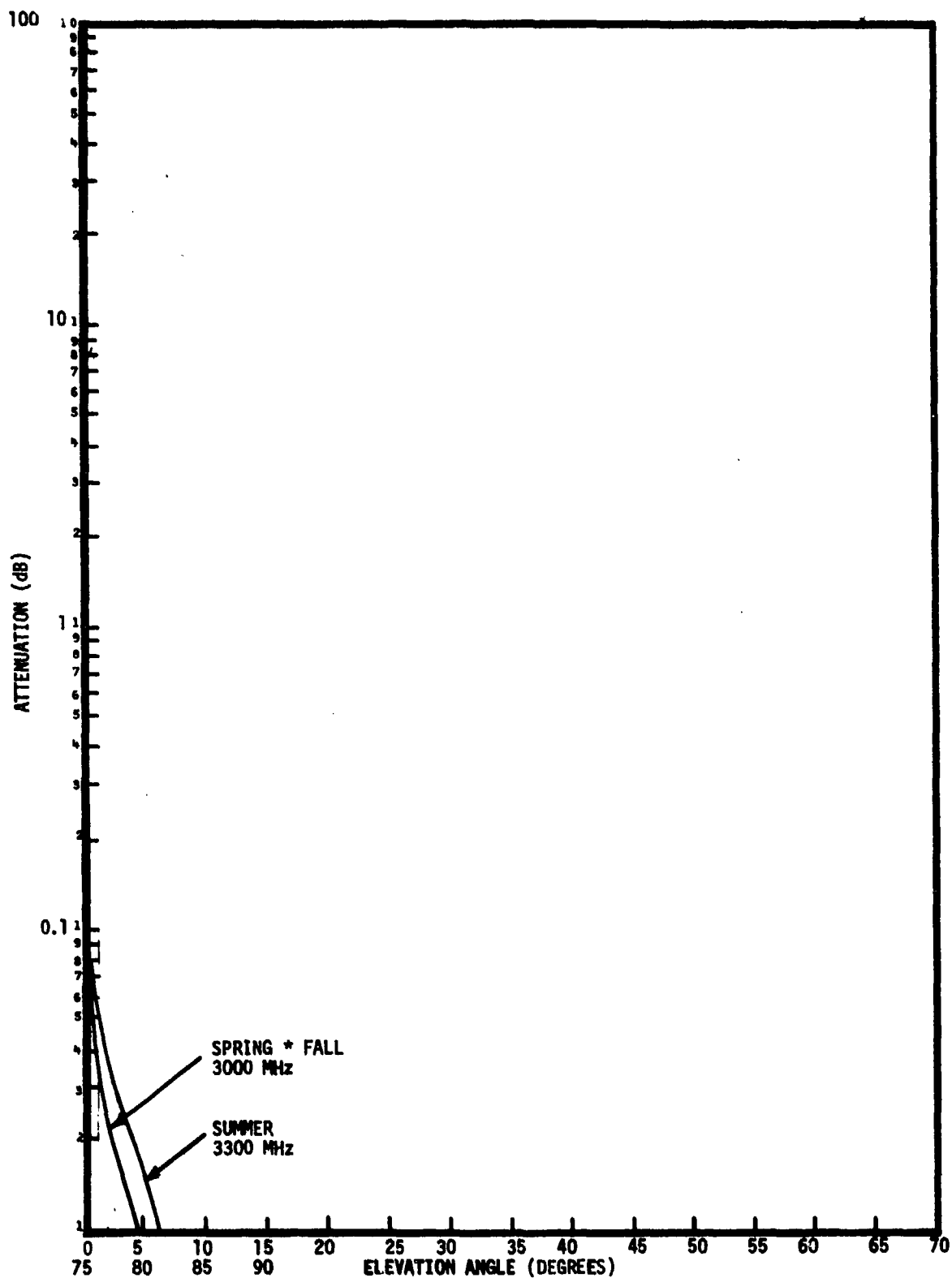
Figure 8. Attenuation vs Elevation Angle for Moderate Rain
(4.0 mm/hr)
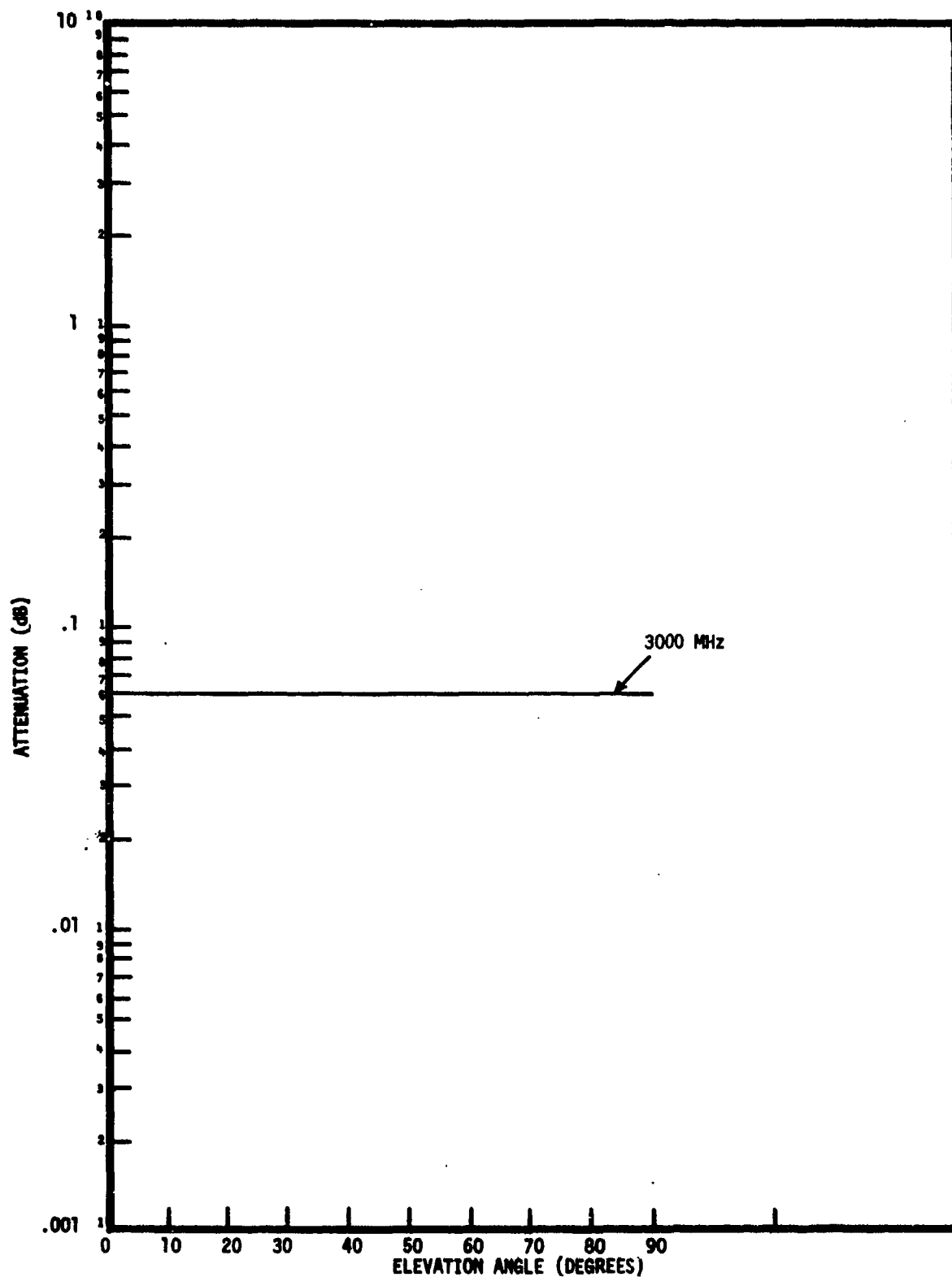
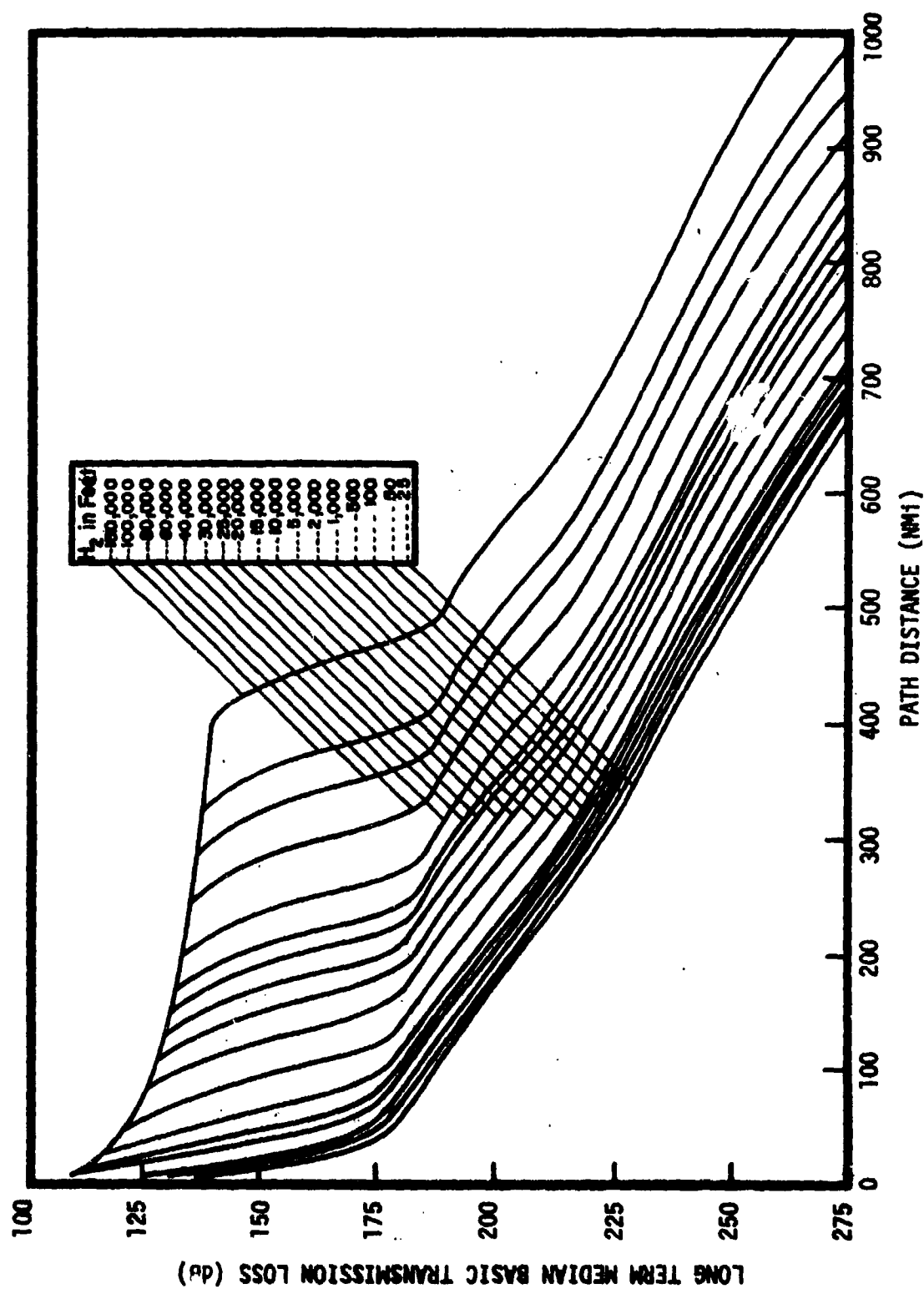Figure 9. Attenuation vs Elevation Angle for Heavy Rain
(16 mm/hr)
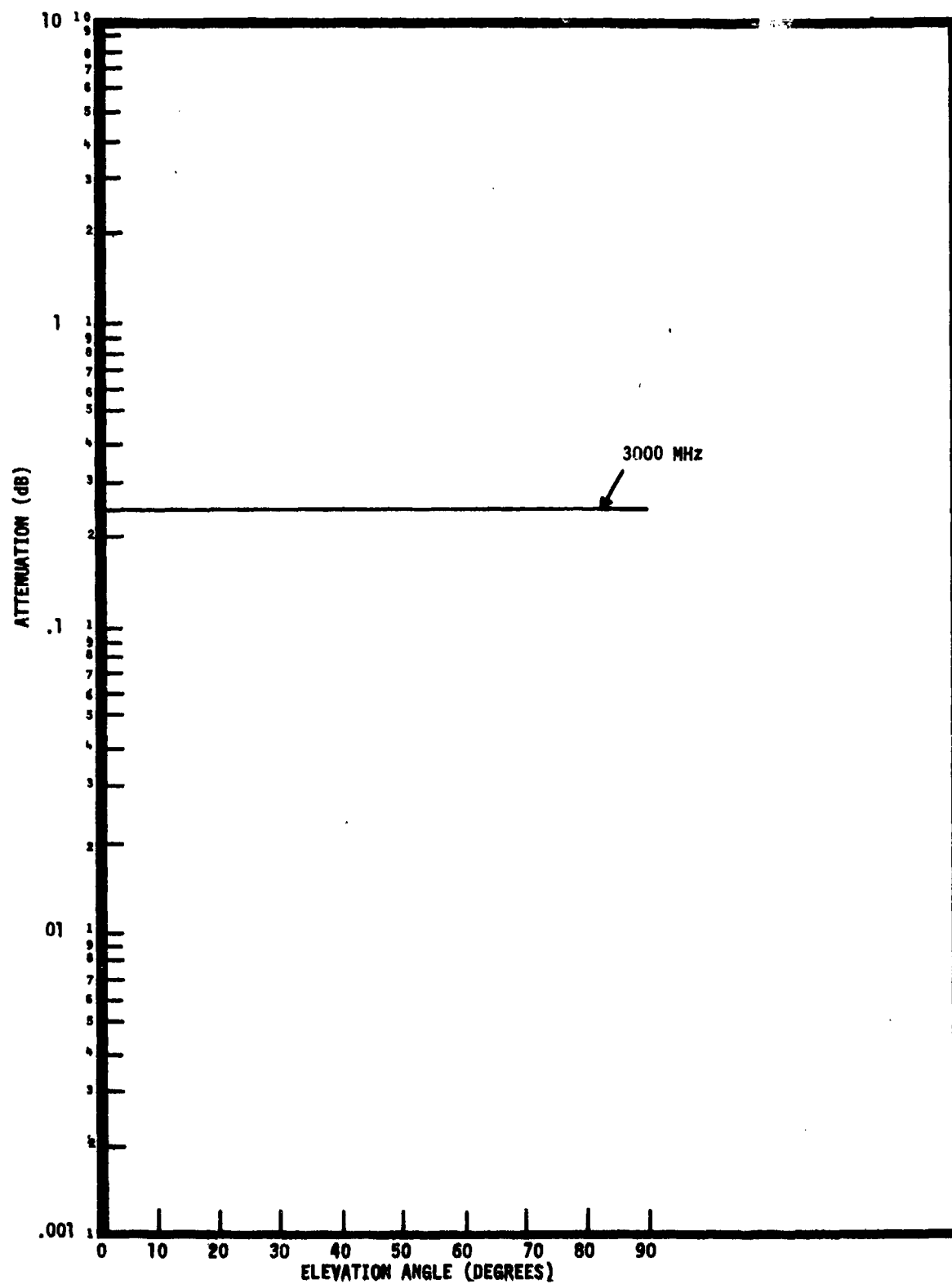
Figure 10. Attenuation vs Elevation Angle for Very Heavy Rain
(100 mm/hr)

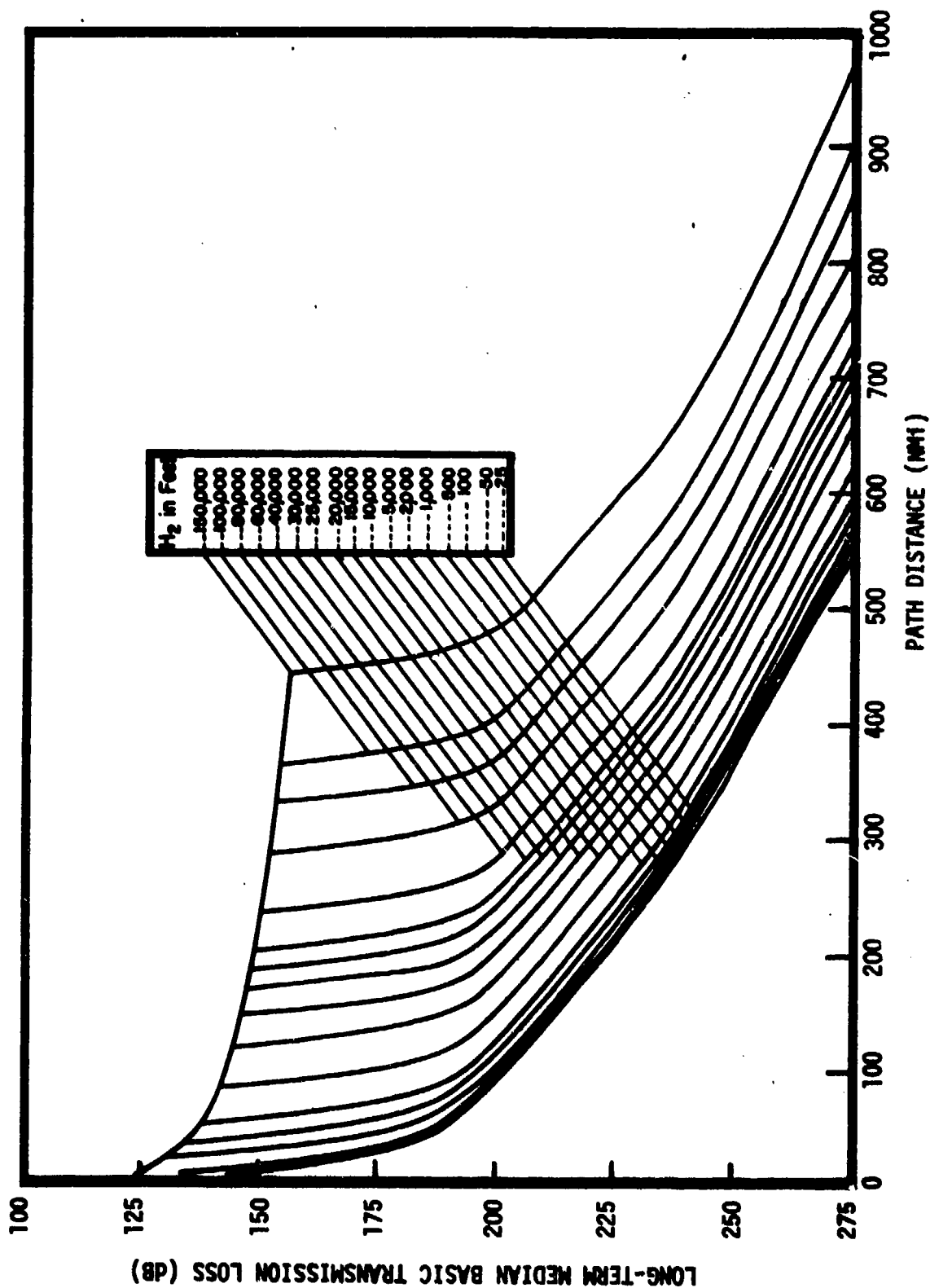Figure 11. Basic Transmission Loss vs Distance; F = 300 MHz,
H$_1$ = 25 ft.

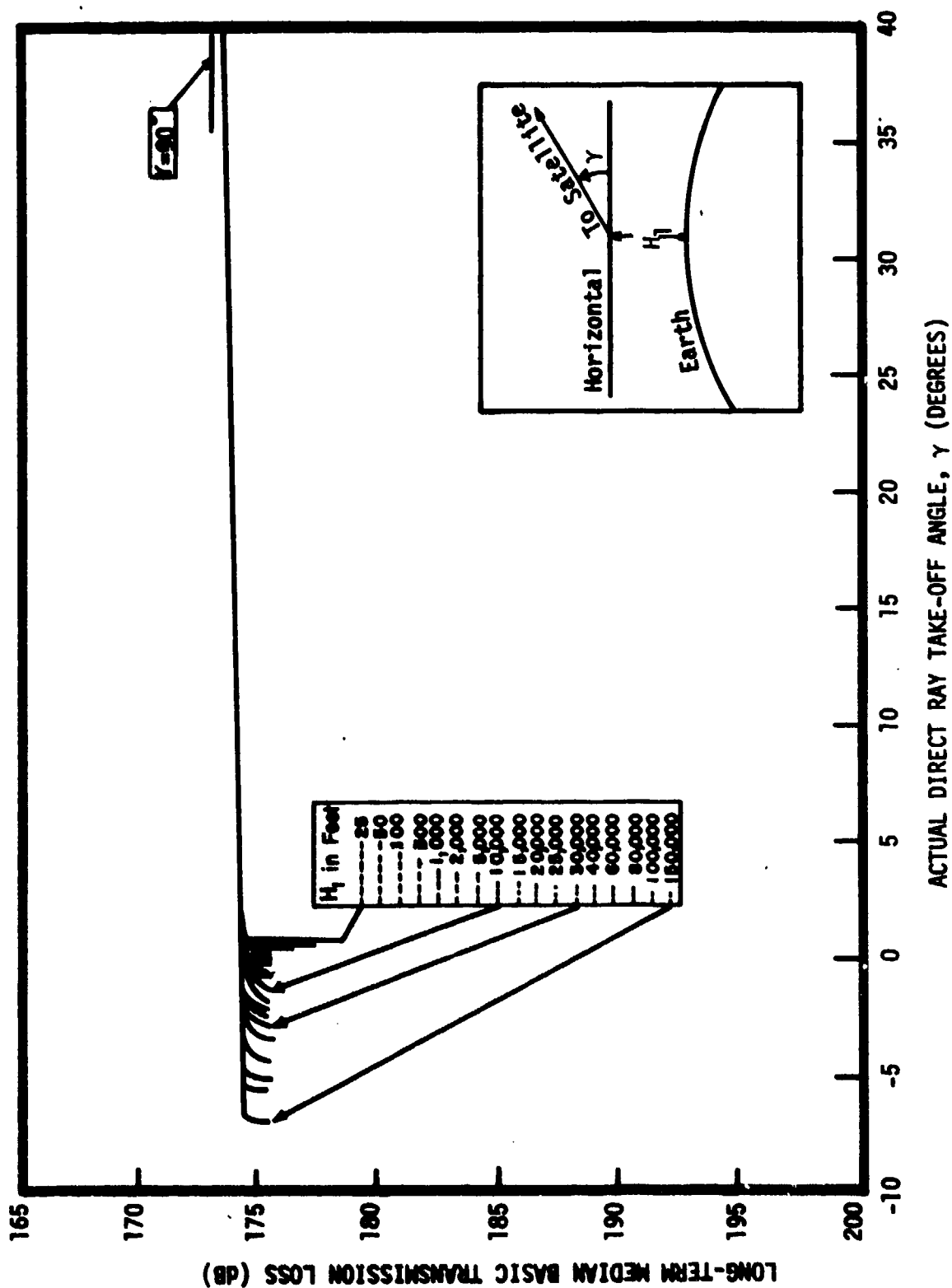Figure 12. Basic Transmission Loss vs Distance; F = 1.6 GHz, H_1 = 25 ft.

Figure 13. Basic Transmission Loss vs Angle; F = 300 MHz,
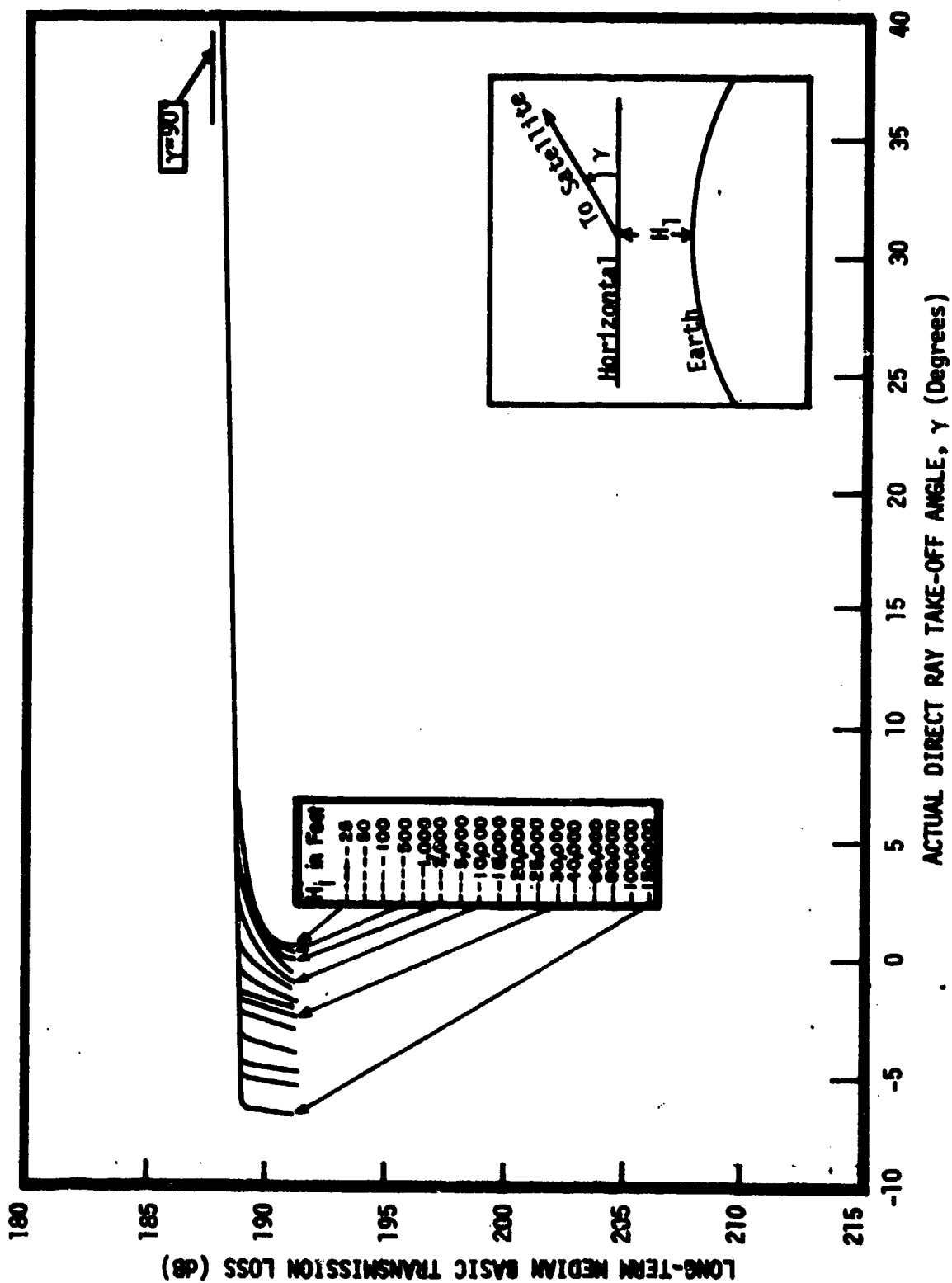H_2 = Synchronous Altitude

Figure 14. Basic Transmission Loss vs Angle; F = 1.6 GHz,
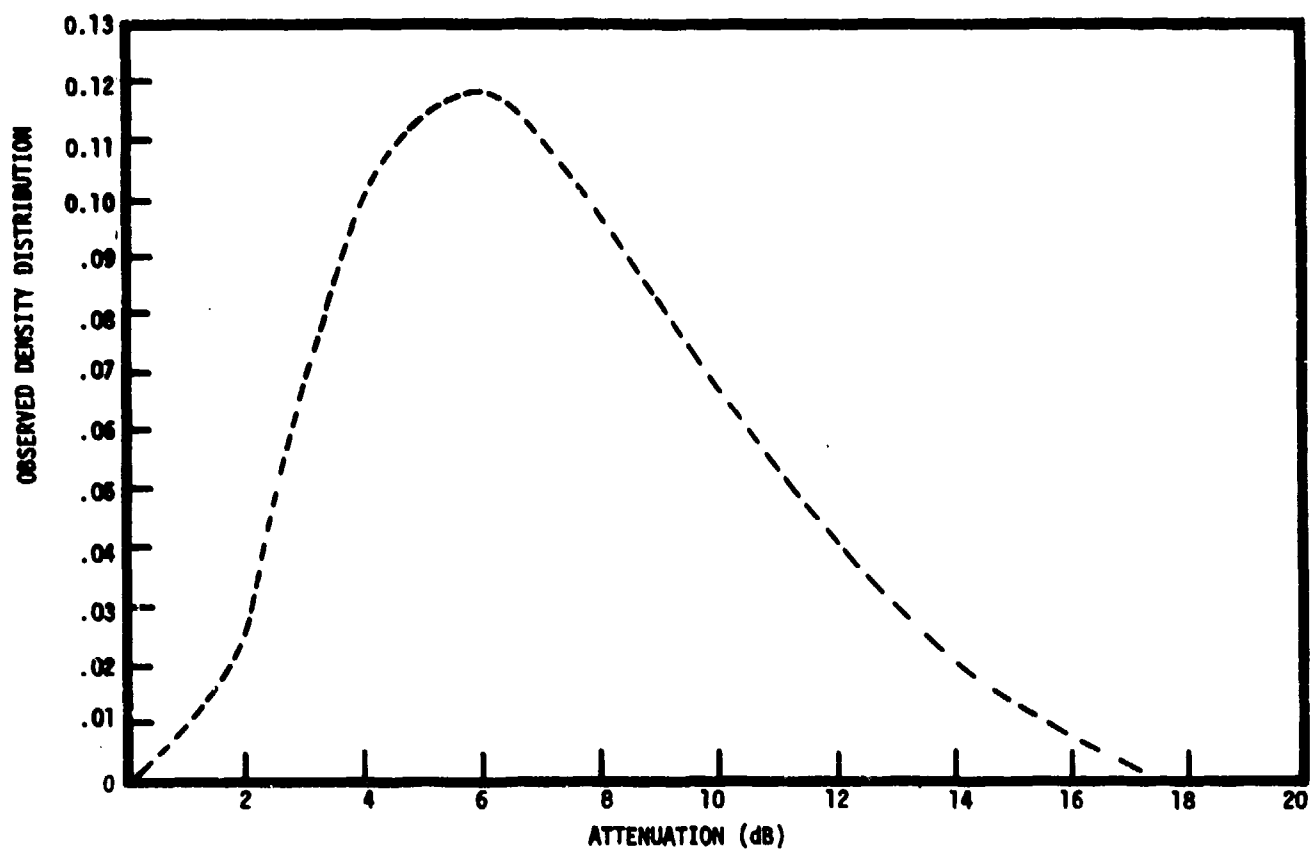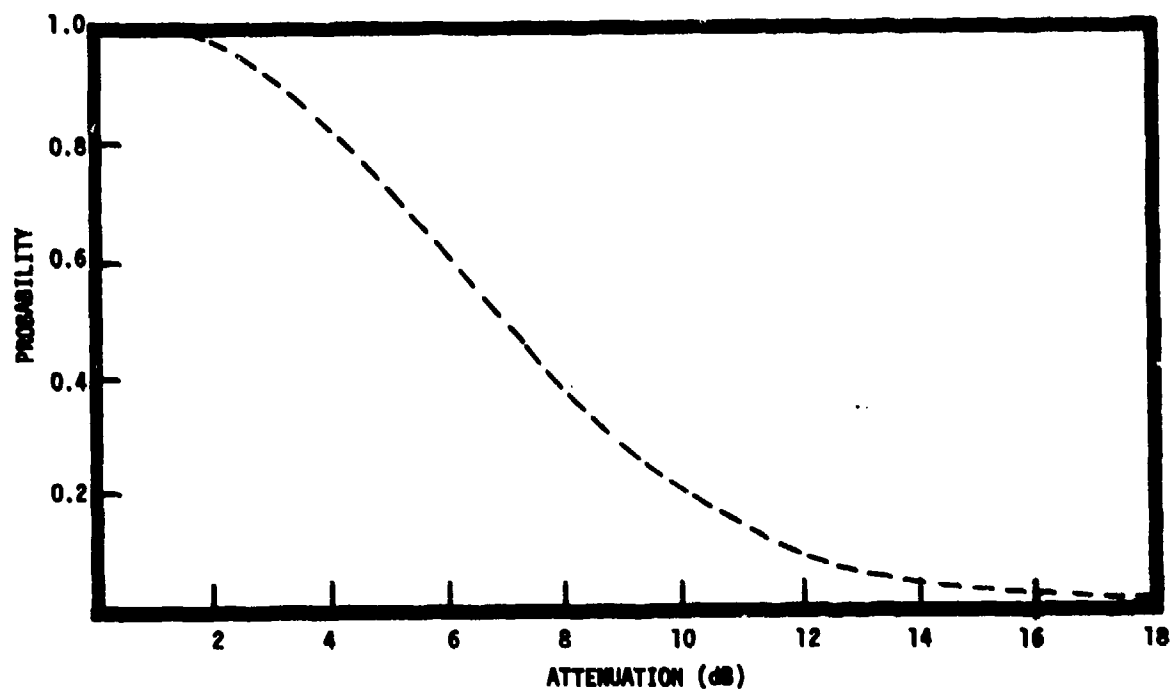H_2 = Synchronous Altitude

Figure 15.   First Trial With LES-6

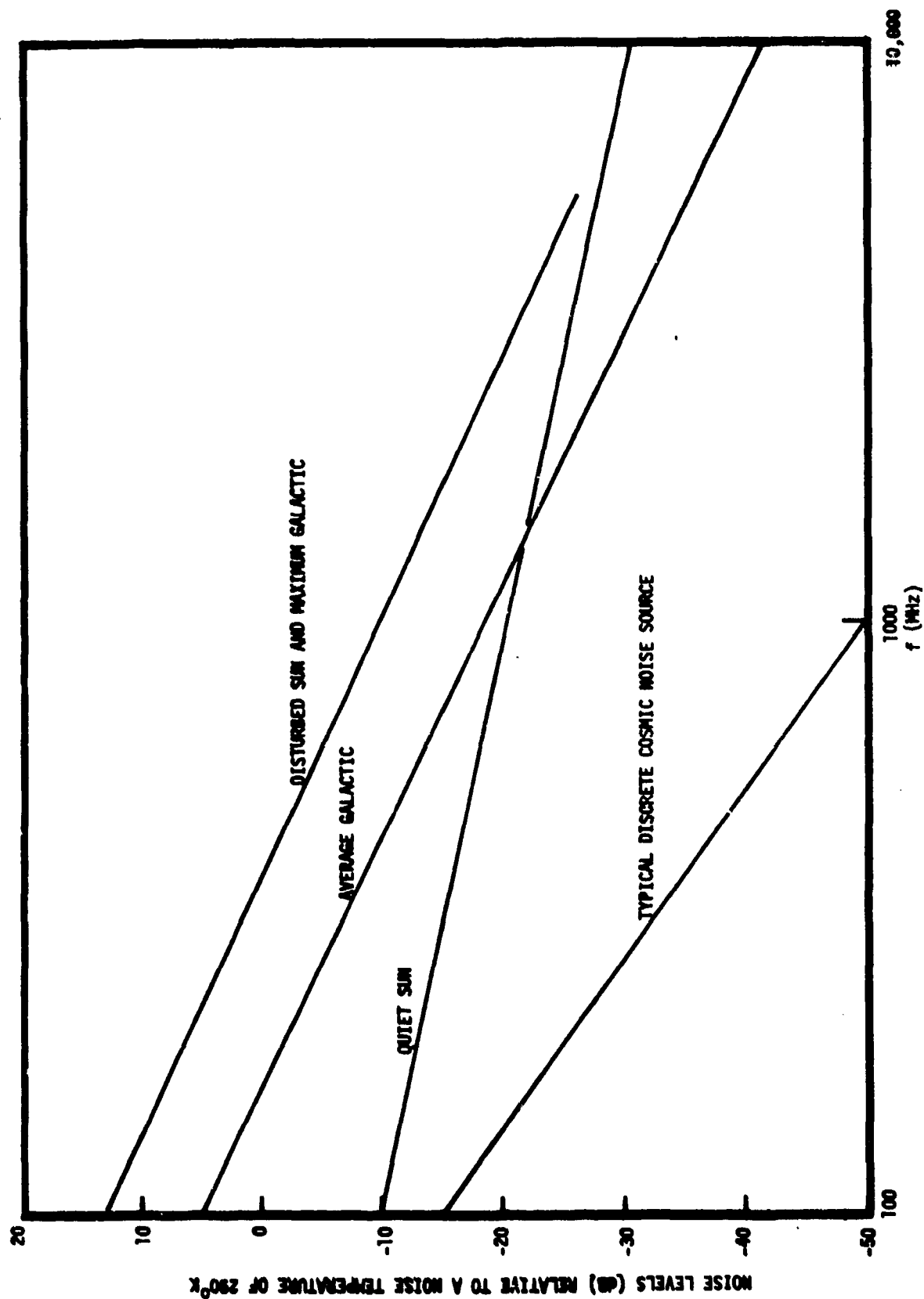Figure 16.   First Trial With LES-6, Cumulative Distribution
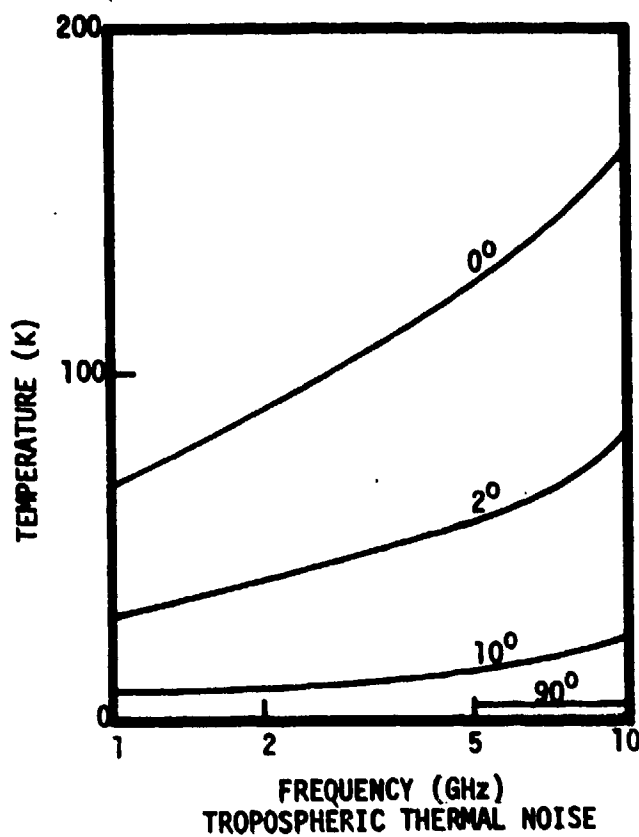
Figure 17. Galactic and Solar Noise Levels for a λ/2 Dipole Receiving Antenna

TROPOSPHERIC THERMAL NOISE

Surface Pressure: 760 mg Hg   Surface temperature: 20°C

Water vapor density: 10 g/m^3

Angles of elevation: 0° - 90° as shown

Figure 18. Tropospheric Thermal Noise

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